SPW-1: A Low-Maintenance Wearable Activity Tracker for Residential Monitoring and Healthcare Applications

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Abstract. In this paper, we present SPW-1; a low-profile versatile wearable activity tracker that employs two ultra-low-power accelerometers and relies on Bluetooth Low Energy (BLE) for wireless communication. Aiming for a low maintenance system, SPW-1 is able to offer a battery lifetime of multiple months. Measurements on its wireless performance in a real residential environment with thick brick walls, demonstrate that SPW-1 can fully cover a room and - in most cases - the adjacent room, as well. SPW-1 is a research platform that is aimed to be used both as a data collecting tool for health-oriented studies outside the laboratory, but also for research on wearable technologies and body-centric communications. As a result, SPW-1 incorporates versatile features, such as external sensor support, various powering options, and accelerometer configuration options that can support a wide range applications from kinematics to long-term activity recognition.

Key words: Wearable Technologies, Bluetooth Low Energy, Internet of Things, eHealth, Healthcare Technologies

1 Introduction

The increasing trends in elderly populations [8] and the continuous rise of chronic medical conditions, such as depression and diabetes, push the limits of national health systems [7]. Wearable technologies [5] and Ambient Assisted Living (AAL) infrastructures are widely considered promising directions that could encourage people to monitor their own well-being and facilitate timely interventions.

In addition to health-oriented applications, long-term activity monitoring with wearable technologies is a tool that facilitates health-oriented research. Avon Longitudinal Study of Parents and Children (ALSPAC) is a cohort study of children born in the county of Avon in England. During the first stage of the study in the early 90s, thousands of pregnant women were monitored. More recently, the study continues; monitoring the grandchildren of the originally monitored subjects [19] and the researchers adopt wearable technologies to replace diaries. SPHERE (a Sensor Platform for Healthcare in a Residential Environment) is an interdisciplinary research collaboration that aims to monitor volunteers in their own home environment [25]. Wearable sensors are used, among other sensing modalities, to monitor the everyday behaviour of the users [10].

Long-term activity monitoring outside the laboratory, such as monitoring the activities of daily life in a residential environment, introduces important challenges that typically do not rise in controlled laboratory environments. The employed wearable devices need to be small, lightweight, comfortable and with low maintenance requirements. Contrary to fashionable wearable gadgets, health-oriented technologies cannot depend on the user for regular maintenance, such as recharging or replacing the battery. For instance, patients suffering from mental conditions are not in a position to maintain the technologies that support them. In addition, in health-oriented research studies outside the laboratory, long battery lifetime increases the reliability of data collection, as the problem of data loss, due to improper maintenance of the technologies used, is mitigated.

With the aforementioned requirements as the primary goal, this paper focuses on the design and evaluation SPW-1 (First SPHERE Wearable), a versatile wearable monitoring system shown in Fig. 1. The design is based on two triaxial accelerometers and uses Bluetooth Low Energy (BLE) [4] for wireless communication. Differential measurements from the two accelerometers enable the approximation of angular acceleration and hence an estimation of the angular velocity without the need of employing a power-hungry gyroscope.

SPW-1 is a research platform that is intended to be used both as a data collector for health-oriented studies and healthcare applications, but also for research on wearable computing and body-centric communications. To support long-term monitoring applications outside the laboratory, SPW-1 is small, lightweight, and ultra low power. At the same time, SPW-1 is a versatile research platform. It is fully programmable, compatible with various power sources - including energy harvesters - and supports external sensors and antennas. Moreover, different accelerometer configurations allow the user to trade battery lifetime for data quality, enabling a wide variety of applications ranging from kinematics to long-term activity recognition. The contribution of this work is twofold. Beyond offering a tool to the research community, we provide insight to researchers and engineers who are developing similar systems. In particular, we provide a thorough energy consumption study that is the basis of meaningful battery lifetime estimations for different sensor configurations. Moreover, we study SPW-1's wireless performance in the context of body-centric communications. The study includes measurements both in a controlled (*i.e.* anechoic chamber) and in a residential environment.

The remainder of the paper is organised as follows. Section 2 summarises the related work; Section 3 presents the system design of SPW-1; Section 4 evaluates its performance; and Section 5 concludes the paper.

2 Related Work

In recent years fashionable gadgets, such as Fitbit, Jawbone UP and Nike+ Fuelband SE, have appeared in the consumer electronics market [14]. Such fitness devices demonstrate the rise of a trend towards self-monitoring, as well as the willingness of users to wear them. However, commercial gadgets are of limited use for research or medical applications due to limited access to the raw data, their lack of interoperability with other healthcare systems and their limited expandability to new sensor technologies. Furthermore, their need for regular recharging (typical battery lifetime of less than a week) hinders their suitability for target groups that are uncomfortable with or physically unable of managing modern technologies.

The research community has also used several wearable devices for activity monitoring, a few of which are briefly reviewed in this paper. We refer the reader to [5] for an exhaustive survey on smart wearable technologies. Verity [24] is an AAL platform that is using a wearable device equipped with an accelerometer and a piezo-resistive sensor for fall detection and heart rate monitoring. In [11], the authors propose an AAL platform based on a waist-worn accelerometer that is able to identify basic activities, such as sitting, walking, running and jumping. Similarly, [26] and [6] perform identification of basic activities using multiple on-body accelerometers and gyroscopes. These platforms use off-the-shelf hardware and do not focus on their power consumption, resulting to wearable devices that require regular recharging. Other works present low power hardware that target various body sensing applications by incorporating different types of sensors, such as bio-impedance sensors [15], microphones [18] and inertial sensors [12].

On a different perspective, related work on Wireless Body Area Networks (WBANs) typically focuses on the networking aspects of body sensor networks[23].

3 System Design

SPW-1 is a research platform that is designed on two key principles. The primary design goal is ultra low power consumption and user acceptance. Indeed, a long battery lifetime may be considered fundamental for long-term monitoring. Furthermore, it is not desirable for the platform to depend on the user for maintenance. The secondary design goal is versatility. As a research platform, SPW-1 should be able to support different types of research that range from health-oriented studies to body-centric communications.

SPW-1 is designed with the wrist as the target body position. We consider a wrist-mounted device as the most socially-acceptable and least invasive choice to the subject's everyday routine, due to the fact that people of both sexes commonly wear wrist-worn gadgets, such as watches and bracelets. Alternative positions, such as the chest or the waist, can be realised via an appropriate enclosure, but hold the risk of being removed by the subject and compromising the effectiveness of the system. Social studies [27][3] have shown the importance of wearable devices being comfortable and not intrusive to the daily life activities. In [16], the authors assess various body positions and present comparison results in which the wrist ranks high in all the considered activities in terms of classification accuracy.

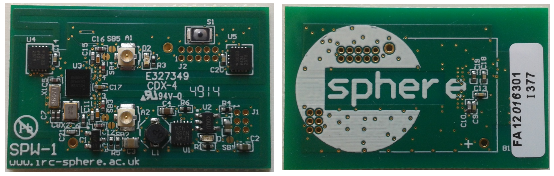

Fig. 1. SPW-1: Top view (left) and bottom view (right) of the circuit board.

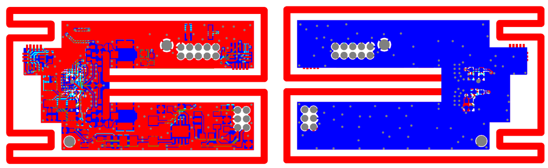

Fig. 2. SPW-1: Top copper layer (left) and bottom copper layer (right) of the circuit board. The differentially-fed loop antenna is printed around the other components.

Fig. 1 shows the printed circuit board (PCB), with dimensions of $24 \times 39 \times 3.8$ mm. The core component is a nRF51822 system-on-chip (SoC) which incorporates a ARM Cortex M0 microcontroller unit (MCU), 32KB of RAM, 256KB of non-volatile flash memory, and a BLE radio (a comparison study of BLE and ZigBee can be found in [20]). Two ADXL362 accelerometers are interfaced, over SPI (Serial Peripheral Interface), to the nRF51822 core. The ADXL362 is a micro-power triaxial digital accelerometer that has 12-bit resolution, a maximum sampling frequency of 400 Hz, and supports measurement ranges of $\pm$2g, $\pm$4g, $\pm$8g. It also employs a 512-sample FIFO buffer (First In First Out). We refer the reader to [2] for figures on the measurement noise levels and their variation with temperature. The incorporation of two accelerometers, at a distance of 30 mm, provides a low power alternative to a gyroscope. Indeed, differential measurements from multiple accelerometers can be used to derive the angular acceleration [21]. The accelerometers are powered by the MCU through its GPIO (General Purpose Input Output) pins and hence is able to power them on and off individually. Therefore, the use of the second accelerometer is optional. The ADXL362 also provides two interrupt pins (INT1 and INT2) that can be used either to generate interrupts on events, or to generate events based on external triggers. The two INT1 pins of the accelerometers are connected to GPIO pins of nRF51822 with the purpose of generating interrupts that wake up the MCU. The two INT2 pins are connected, over the same bus, to a GPIO of the MCU as an input. Using INT2, the MCU generates a square wave signal that synchronises the accelerometers by triggering the measurements. The use of the interrupts is also optional.

Regarding powering options, SPW-1 is compatible with various sources. Ultra low power consumption is partially achieved by using the MCU in low power mode, *i.e.* at 1.8V. The system employs the LTC3388 DCDC (Direct Current to Direct Current) converter that efficiently converts any voltage source from 2.7V to 6V, to the required 1.8V. Thus, converter supports multiple options, including 3V coin cell batteries (such as CR2032), 3.7V rechargeable Lithium-Polymer (Li-Po) batteries, and super capacitors. Moreover, SPW-1 is energy harvesting ready, in the sense that any harvester that works at the appropriate voltage level, is compatible. The converter can be also bypassed, as the board provides direct access to the 1.8V trail. SPW-1 also employs an MCP73831, a 500 mA linear charge management controller with 4.2V output that is compatible with single cell 3.7V Li-Po batteries. The battery charger is, by default, isolated from the remaining of the circuit and can be optionally connected.

With regard to input and output interfaces, SPW-1 employs one button and two LEDs (Light Emitting Diodes). The button and one of the LEDs are controlled by the MCU and, thus, are available to the application. The other LED is connected to the battery charger indicating when the battery is charging. Moreover, external sensors can be connected to SPW-1, using 7 available GPIOs (all support digital inputs; 2 of them also support analogue inputs). The INT2 line of the accelerometers is also externally available, so that external sensors can be synchronised to the embedded accelerometers. Lastly, the board also employs a Serial Wire Debug (SWD) interface for programming and debugging.

Energy awareness is also considered in the design. With a potential divider, the high voltage of the source is appropriately conditioned to the requirements of the MCU's analogue-to-digital converter (ADC). When a battery (*e.g.* CR2025) is used, this feature can be used to issue low-battery warnings. In case of energy harvesting, energy-awareness allows the system to adapt to the available ambient energy.

As far as wireless is concerned, SPW-1 employs a meandered loop antenna printed on the FR4 substrate, matched to the differential RF output of the nRF51822 (shown in Fig. 2). The loop antenna was measured to have an efficiency of about 60% (relative to a high-efficient reference antenna) and a maximum directivity of 7 dBi (computed from the measured 3D radiation pattern). The antenna was measured in isolation in an anechoic chamber. A comparison of the wireless performance of SPW-1 to the reference design that employs a printed monopole antenna (and hence not using the differential RF output of the chip) is discussed in Section 4.2. Furthermore, SPW-1 supports external antennas by incorporating u.FL connectors. Using solder-bridges, the user can select either the embedded loop antenna or external antennas. The radio of the nRF51822 supports 7 transmission power levels ranging from -20 dBm to 4 dBm. The experiments, presented in Section 4, quantify the effect of this setting with respect to trade-off between energy consumption and wireless coverage.

4 System Evaluation

In this section, we evaluate the performance of SPW-1. First, we focus on measuring the energy consumption of fundamental system events, and on providing realistic battery lifetime estimations. Then, we measure the wireless performance in both an anechoic chamber and a house. The latter identifies the wireless coverage capabilities of SPW-1 in residential environments with thick brick walls.

4.1 Energy Consumption and Battery Lifetime Estimations

In this section, we benchmark SPW-1 against the reference design of the nRF51822 radio, *i.e.* the nRF51822-DK [17]. By incorporating the LTC3388 DCDC converter, SPW-1 yields lower power consumption than the reference design. The nRF51822-DK uses, instead, the nRF51822's internal linear regulator.

For the nRF51822-DK, the continuous idle power consumption is measured with a multimeter, configured as an ammeter and positioned in series with the positive side of the power supply. For this test, the nRF51822 is programmed to be in sleep mode and both accelerometers are disabled through the GPIOs. We measured a constant current of 5 μA. Because of its linear voltage regulation, the power consumption scales linearly with the supply voltage. Considering the typical battery voltage levels 3V and 3.7V, the idle power consumption is 15 μW and 18 μW, respectively. For SPW-1, the idle power consumption is not continuous. Instead, the DCDC converter consumes energy periodically keeping its output voltage above the target threshold. Hence, we measured the idle power consumption by measuring and multiplying the energy consumed during one duty cycle by their frequency. The energy of a duty cycle of the converter was measured with a series 10 Ω resistor and an oscilloscope, as in [9]. At both voltage levels, we measure a constant idle power consumption of 8.4 μW, 46% less than the reference kit, when using a 3V coin cell battery.

To measure the processing power consumption, both platforms were programmed to perform some dummy processing cycles (integer multiplication and addition). In a similar fashion, the current was measured with a series 10 Ω resistor on the positive side of the power supply. The results demonstrate again the benefits of the DCDC converter. Considering a 3V and a 3.7V battery, the reference kit consumes 18 mW and 22.2 mW for processing respectively. SPW-1, on the other hand, consumes 9.5 mW at both voltage levels.

Next, we measure the energy required by the radio for transmitting data. In particular, we measure the energy consumption of a triple advertisement (*i.e.* 3 packets of 39 bytes) at all different transmission power levels. The current profile of the advertisement event was captured with a series 10 Ω resistor. The energy is then derived by estimating the integral of the current profile and multiplying it by the supply voltage. Fig. 3 demonstrates that SPW-1 is 20% more energy-efficient than the reference design when using 4 dBm transmission power and a 3V battery. The figure also shows how the energy consumption scales with the transmission power level, indicating that significant energy savings can be achieved by turning the power level down to 0 dBm and -4 dBm.

To facilitate realistic battery lifetime estimations, we also provide the power consumption of the peripherals. Each accelerometer adds an extra constant power consumption of approximately 3 μW. Transferring the data from the FIFO buffer of ADXL362 to the memory of the MCU takes approximately 13 ms (SPI clock at 4 MHz), resulting to a consumption of approximately 135.5 μJ.

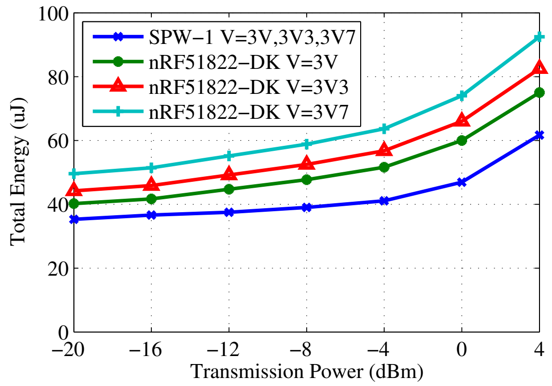

Fig. 3. Energy consumption for the transmission of a BLE triple advertisement.

Transferring a single acceleration sample from the accelerometer to the MCU consumes approximately 1.9 μJ (in contrast to 3.6 μJ for nRF51822-DK). The LED consumes 1.6 mW when turned on.

Next, we combine the consumption measurements in an attempt to provide realistic battery lifetime estimations, based on an indicative scenario. Such estimations demonstrate how the lifetime of the battery scales with the configuration of different parameters, such as the number of accelerometers, the resolution and the sampling frequency. The battery lifetime estimations are based on the following equation:

$$T = \frac{E_{BAT}}{P_I + P_{XL} \times N + (E_{SPI} + E_{BLE}) \times f_s \times N} , \quad (1)$$

where E_{BAT} is the total energy of the battery; P_I is the idle power consumption; P_{XL} is the power consumption of a single accelerometer; E_{SPI} is the energy consumed for transferring a single acceleration sample over SPI from the accelerometer to the MCU; E_{BLE} is the energy consumed for the transmission of a single sample over BLE given by Fig. 3 and divided by the number of samples inside a packet; f_s is the sampling frequency; and N is the number of accelerometers.

In particular, we consider a scenario where SPW-1 streams raw accelerometer data using the undirected connectionless BLE advertisements (similarly to [10]). Although data reliability can be addressed at the receiver [22], this communication approach does not provide delivery guarantees and, thus, can be only applied to applications that can tolerate data loss or make use of specific missing data techniques [13]. We also assume the following. We assume that for resilience to interference all three advertisement packets are populated with the same payload. We further assume the maximum BLE packet size of 39 bytes (24 bytes of payload), which provides necessary space for either 4 triaxial samples of 12-bit resolution or 8 triaxial samples of 8-bit resolution; and that the SPI bus between the accelerometers and the MCU is clocked at 4 MHz. Lastly, we assume that the system is powered by a 210 mAh coin cell battery (3V).

Table 1. Battery Lifetime Approximations in Days

Tx Power	Freq. (Hz)	1 Accelerometer		2 Accelerometers	
		8-bit	12-bit	8-bit	12-bit
4 dBm	1	1174	873	750	520
	10	240	140	125	72
	20	127	72	65	36
	50	53	29	26	14
-4 dBm	1	1328	1054	879	654
	10	314	194	167	101
	20	170	102	87	52
	50	71	42	36	21

Table 1 shows the battery lifetime estimations, in days, assuming different configuration scenarios. The frequency column represents the sampling frequency of the accelerometer(s). Notice that the battery lifetime ranges from few weeks to few years, depending on the configuration. Observe that at high sampling frequencies the energy consumption is dominated by frequent duty cycles. At low sampling frequencies, instead, the idle consumption becomes increasingly more important. In [16], the authors use accelerometers with 8-bit resolution to perform activity classification. Experimenting with different sampling frequencies, the authors show that the performance of the classifier reaches a high level at approximately 10 Hz with only marginal improvement at higher frequencies. In this configuration, the battery lifetime of SPW-1 is approximated at 240 days. For comparison, using the same methodology, the reference design yields a battery lifetime of approximately 172 days for the same configuration (an improvement of 40%).

4.2 Wireless Performance

In this section, we evaluate SPW-1's wireless performance. We, first, benchmark it against the reference design (nRF51822-DK employs a PCB monopole antenna) in an anechoic chamber. In particular, both wearable sensor units were mounted on a ground plane. At the other side of the room, at a distance of 4.4 m, a receiver unit with two orthogonally polarised patch antennas was used [10]. In both cases, the transmitter was programmed to transmit advertisement packets at a period of 100 ms (4 dBm transmission power). The receiver unit was programmed to log the RSSI of all the received packets. In both experiments, the position of the receiver was fixed while two motors rotated the wearable device through all angles in 3D space. Fig. 4 plots the CDF (cumulative distributed function) of the RSSI of all the packets received for SPW-1 and the reference kit. Observe that, in a controlled environment, SPW-1 performs 2 dB better than nRF51822 in the median case. Overall, despite the significantly lower size (*i.e.* less ground plane, and less isolation between the antenna and surrounding components), SPW-1 maintains the same level of wireless performance.

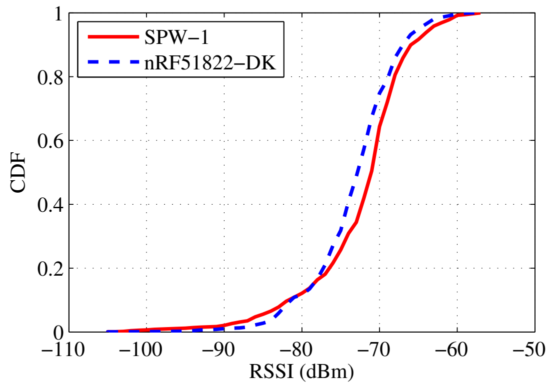

Fig. 4. Comparison of the wireless performance of SPW-1 to nRF51822-DK in the anechoic chamber.

We, next, evaluate the wireless performance of SPW-1 in a residential environment. Specifically, the following experiments were conducted in a typical house in the city of Bristol, UK. In each one of two adjacent rooms, we deployed a receiver unit identical to the ones used in the previous experiment. SPW-1, also programmed as in the previous experiment (*i.e.* 4 dBm transmission power), was mounted on the wrist of a human, who was performing random walks and random activities within the room for approximately 10 minutes (room size: 3×3 m). Therefore, the measurements capture the effect of body shadowing and multipath propagation in a wide variety of situations. Fig. 5 shows the CDF of the RSSI of all the received packets, as measured from the receivers located in the same room and the adjacent room respectively. At the maximum transmission power setting, observe that in the case of the same room, the median is at -68 dBm; whereas, in the adjacent room, the median is at -84 dBm. In the same figure, we also plot the packet error rate (PER) of a nRF51822 receiver for different RSSI values. Assuming an acceptable PER threshold of 5%, we observe that SPW-1 can fully cover a single room (99.9% of the cases) and 87.2% of the cases of the adjacent room. The wireless performance at lower transmission power levels can be approximated by shifting the CDFs in the x-axis accordingly. For instance, if single room coverage is sufficient for a given application, the transmission power could be set to -4 dBm. This configuration yields 33% less energy consumption for transmission (see Fig. 3 and Table 1), covering 98.6% of the single room cases with a PER of less than 5%.

For reference, a performance comparison study of other antennas in the same environment can be found in our previous work [1].

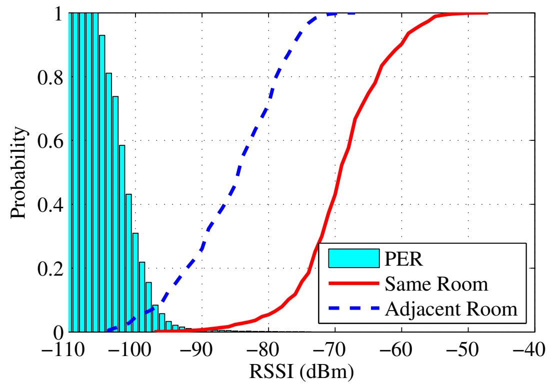

Fig. 5. Wireless performance in the a residential environment.

5 Conclusion

SPW-1 is a wearable activity monitor that is based on two accelerometers for activity sensing and BLE for wireless communication. As a research platform, SPW-1 has multiple purposes with different requirements. Primarily, it is meant to be used as a lightweight and low-profile data collection tool for long-term activity monitoring outside the laboratory. To decrease the dependency on user maintenance, long battery lifetimes are required. Furthermore, access to the raw data and to the accelerometer configuration settings is also fundamental. Moreover, SPW-1 supports external sensors and external antennas to facilitate research on wearable computing and body-centric communications.

Ultra low energy consumption is a primary design goal. SPW-1 embeds two accelerometers that may function as an energy-efficient alternative to a gyroscope. We measured the consumption of SPW-1 and benchmarked it against the off-the-shelf nRF51822-DK. The comparison demonstrates significant improvements. Assuming the use of a 3V coin cell battery (CR2032), SPW-1 consumes approximately 45% less power for processing and in idle mode, and 20% less energy for wireless transmission. Battery lifetime estimations in a indicative scenario demonstrate the dependency of the battery lifetime to the configuration settings of the accelerometers (estimations range from weeks to years). For example, assuming 210 mAh battery capacity, a configuration used in [16] yields a battery lifetime estimation of 240 days.

Wireless performance is also fundamental, especially in residential monitoring. Controlled measurements, in an anechoic chamber, benchmark the wireless performance of SPW-1, demonstrating a 2 dB marginal improvement with regards to the reference design, despite its significantly smaller size. In addition, we performed measurements in a residential environment with thick brick walls, in which SPW-1 was mounted on the wrist of a user that was performing random activities and random walks within a 9 m^2 room. In this scenario, SPW-1 was able to fully cover a single room (99.9% of the cases) and 87.2% of the cases of the adjacent room with a PER of less than 5%. The presented experiments also quantify the trade-off between wireless coverage and energy consumption. For instance, in scenarios where only single room coverage is required, a lower transmission power setting can yield 33% less energy consumption for transmission, covering 98.6% of the single room cases with a PER of less than 5%.

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References

1. Abdullah, M.W., Fafoutis, X., Mellios, E., Klemm, M., Hilton, G.: Investigation into Off-Body Links for Wrist Mounted Antennas in Bluetooth Systems. In: Proc. Loughborough Antennas and Propagation Conf. (LAPC) (2015)
2. Analod Devices: ADXL362 - Micropower, 3-Axis, ±2 g / ±4 g / ±8 g, Digital Output MEMS Accelerometer, Rev. B (2013)
3. Bergmann, J., McGregor, A.: Body-worn sensor design: What do patients and clinicians want? Ann. Biomedical Eng. 39(9) (2011)
4. Bluetooth SIG: Specification of the Bluetooth System - Covered Core Package version: 4.0 (2010)
5. Chan, M., Estève, D., Fourniols, J.Y., Escriba, C., Campo, E.: Smart wearable systems: current status and future challenges. Artif. Intell. Med. 56(3), 137–56 (Nov 2012)
6. Cheng, J., Chen, X., Shen, M.: A framework for daily activity monitoring and fall detection based on surface electromyography and accelerometer signals. IEEE J. Biomedical and Health Informatics 17(1), 38–45 (Jan 2013)
7. Cruz-Jentoft, A.J., Franco, A., Sommer, P., Baeyens, J.P., Jankowska, E., Maggi, A., Ponikowski, P., Rys, A., Szczerbinska, K., Michel, J.P., Milewicz, A.: Silver paper: the future of health promotion and preventive actions, basic research, and clinical aspects of age-related disease–a report of the European Summit on Age-Related Disease. Aging Clin. Exp. Res. 21(6), 376–385 (2009)
8. Department of Economic and Social Affairs - United Nations: World Population Ageing: 1950-2050. Tech. rep. (2011)
9. Fafoutis, X., Di Mauro, A., Dragoni, N.: Sustainable medium access control: Implementation and evaluation of odmac. In: Proc. IEEE Int. Conf. on Commun. Workshops (ICC). pp. 407–412 (June 2013)
10. Fafoutis, X., Tsimbalo, E., Mellios, E., Hilton, G., Piechocki, R., Craddock, I.: A residential maintenance-free long-term activity monitoring system for healthcare applications. EURASIP Journal on Wireless Communications and Networking 2016(31) (Jan 2016)

11. Gupta, P., Dallas, T.: Feature Selection and Activity Recognition System Using a Single Triaxial Accelerometer. IEEE Trans. Biomedical Engineering 61(6), 1780–1786 (2014)
12. Kan, Y.C., Chen, C.K.: A Wearable Inertial Sensor Node for Body Motion Analysis. IEEE Sens. J. 12(3), 651–657 (Mar 2012)
13. Karadogan, S., Marchegiani, L., Hansen, L., Larsen, J.: How efficient is estimation with missing data? In: Proc. 2011 IEEE Int. Conf. on Acoustics, Speech and Signal Processing (ICASSP). pp. 2260–2263. IEEE (2011)
14. Kooiman, T.J.M., Dontje, M.L., Sprenger, S.R., Krijnen, W.P., van der Schans, C.P., de Groot, M.: Reliability and validity of ten consumer activity trackers. BMC Sports Sci. Med. Rehabil. 7(1), 24 (Jan 2015)
15. Lee, S., Polito, S., Agell, C., Mitra, S., Firat Yazicioglu, R., Riistama, J., Habetha, J., Penders, J.: A Low-power and Compact-sized Wearable Bio-impedance Monitor with Wireless Connectivity. J. Phys. Conf. Ser. 434(1), 012013 (Apr 2013)
16. Maurer, U., Smailagic, A., Siewiorek, D., Deisher, M.: Activity recognition and monitoring using multiple sensors on different body positions. In: Int. Workshop on Wearable and Implantable Body Sensor Networks (BSN) (2006)
17. Nordic Semi.: nRF51822 Development Kit - User Guide v1.4 (2013)
18. Oletic, D., Arsenali, B., Bilas, V.: Low-power wearable respiratory sound sensing. Sensors (Basel). 14(4), 6535–66 (Jan 2014)
19. Pearson, H.: Children of the 90s: Coming of age. Nature 484, 155–158 (2012)
20. Siekkinen, M., Hiienkari, M., Nurminen, J., Nieminen, J.: How low energy is bluetooth low energy? Comparative measurements with ZigBee/802.15.4. In: Proc. IEEE Wireless Communications and Networking Conference Workshops (WCNCW). pp. 232–237 (2012)
21. Tsai, Y.L., Tu, T.T., Bae, H., Chou, P.: Ecoimu: A dual triaxial-accelerometer inertial measurement unit for wearable applications. In: Proc. Int. Conf. Body Sensor Networks (BSN). pp. 207–212 (June 2010)
22. Tsimbalo, E., Fafoutis, X., Piechocki, R.: Fix It, Dont Bin It! - CRC Error Correction in Bluetooth Low Energy. In: Proc. 2nd IEEE World Forum on Internet of Things (WF-IoT) (2015)
23. Ullah, S., Higgins, H., Braem, B., Latre, B., Blondia, C., Moerman, I., Saleem, S., Rahman, Z., Kwak, K.: A Comprehensive Survey of Wireless Body Area Networks. J. of Medical Systems 36(3), 1065–1094 (2012)
24. Winkley, J., Jiang, P., Jiang, W.: Verity: an ambient assisted living platform. IEEE Trans. Consumer Electronics 58(2), 364–373 (2012)
25. Woznowski, P., Fafoutis, X., Song, T., Hannuna, S., Camplani, M., Tao, L., Paiement, A., Mellios, E., Haghighi, M., Zhu, N., Hilton, G., Damen, D., Burghardt, T., Mirmehdi, M., Piechocki, R., Kaleshi, D., Craddock, I.: A Multi-modal Sensor Infrastructure for Healthcare in a Residential Environment. In: Proc. Int. Conf. Communications (ICC) Workshops (2015)
26. Zhang, Y., Markovic, S., Sapir, I., Wagenaar, R., Little, T.: Continuous functional activity monitoring based on wearable tri-axial accelerometer and gyroscope. In: Proc. 5th Int. Conf. Pervasive Computing Technologies for Healthcare (PervasiveHealth). pp. 370–373 (2011)
27. Ziefle, M., Rocker, C.: Acceptance of pervasive healthcare systems: A comparison of different implementation concepts. In: Proc. 4th Int. Conf. Pervasive Comput. Technologies for Healthcare (PervasiveHealth). pp. 1–6 (2010)